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Human influences superseded climate to disrupt the 20th century fire regime in Jasper National Park, Canada

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ABSTRACT

To enhance understanding of how climate and humans influenced historical fire occurrence in the montane forests of Jasper National Park, we crossdated fire-scar and tree age samples from 172 plots. We tested effects of drought and climatic variation driven by the El Niño-Southern Oscillation (ENSO) and Pacific North American (PNA) pattern on fire occurrence. We also tested whether local droughts were associated with ENSO, PNA, Pacific Decadal Oscillation and Atlantic Multidecadal Oscillation. We used a combination of instrumental and proxy-climate records to test whether climatic variation explained the absence of fire scars in our study area during the 20th century. From 1646 to 1915, 18 fires burned mainly during drier than average years. Drought years, but not fire years, were associated with positive ENSO and PNA indices, corresponding to warmer conditions with reduced snowpacks. Fire frequency varied through time, although no fire scars have formed since 1915. Potential recording trees present at all plots and climate conducive to fire over multiple years provide evidence that human influences superseded climatic variation to explain the lack of fire scars during the 20th century. Fire suppression significantly altered the fire regime after the formation of Jasper National Park, justifying the ongoing mechanical fuel treatments, prescribed and managed wildfires to improve forest resilience to climate change.

1. Introduction

As global warming progresses, fire regimes in forests of western North America are anticipated to include wildfires of increasing number, size and severity, with measurable effects already observed (Flannigan et al., 2003; McKenzie et al., 2004; Westerling, 2016; Wotton et al., 2017). Apart from climate, fire regimes are influenced by land use and fire management (Bowman et al., 2009); however, their effects vary among forests (Schoennagel et al., 2004). Understanding the relative importance of climate and humans and their interacting effects on fire regimes is important for understanding the drivers of variable forest conditions over time at various spatial scales and for developing effective management plans in response to environmental change (Stephens et al., 2013).

Jasper National Park lies along the transition between Montane Cordillera and Boreal Plains ecozones in the Canadian Rocky Mountains (Ecological Stratification Working Group, 1995). In the Park, vegetation varies from grasslands to subalpine forests along steep environmental gradients over short distances. The historical fire regimes also vary with mixed-severity fires in the montane and lower subalpine forests, transitioning to infrequent high-severity fires in the upper subalpine forests. Recent fire history and forest demography reconstructions in montane forests of Jasper showed historical fires burned at a wide range of severities and frequencies (Chavardès and Daniels, 2016). Multiple fire scars on thick-barked interior Douglas-fir (*Pseudotsuga menziesii* var *glauca* (Beissn) Franco) as well as lodgepole pine (*Pinus contorta* Douglas ex Loudon) indicated repeated low-severity fires through time in many stands. Stand-level mean fire return intervals were 30–60 years, but intervals within stands varied from 11 to 165 years. Contemporary stand composition and age structures reflect moderate-to-high severity fires that initiated cohorts in the late 1800s, followed by no fires for most of the 1900s (Chavardès and Daniels, 2016). In absence of fire, documented changes in the 20th century include persistent understory trees that increase the density of montane

Abbreviations: AB, Alberta; AMO, Atlantic Multidecadal Oscillation; c., circa; dbh, diameter at breast height; ENSO, El Niño-Southern Oscillation; JNP, Jasper National Park; m.a.s.l., meters above sea level; PDO, Pacific Decadal Oscillation; PNA, Pacific North American pattern; SEA, superposed epoch analysis; USA, United States of America

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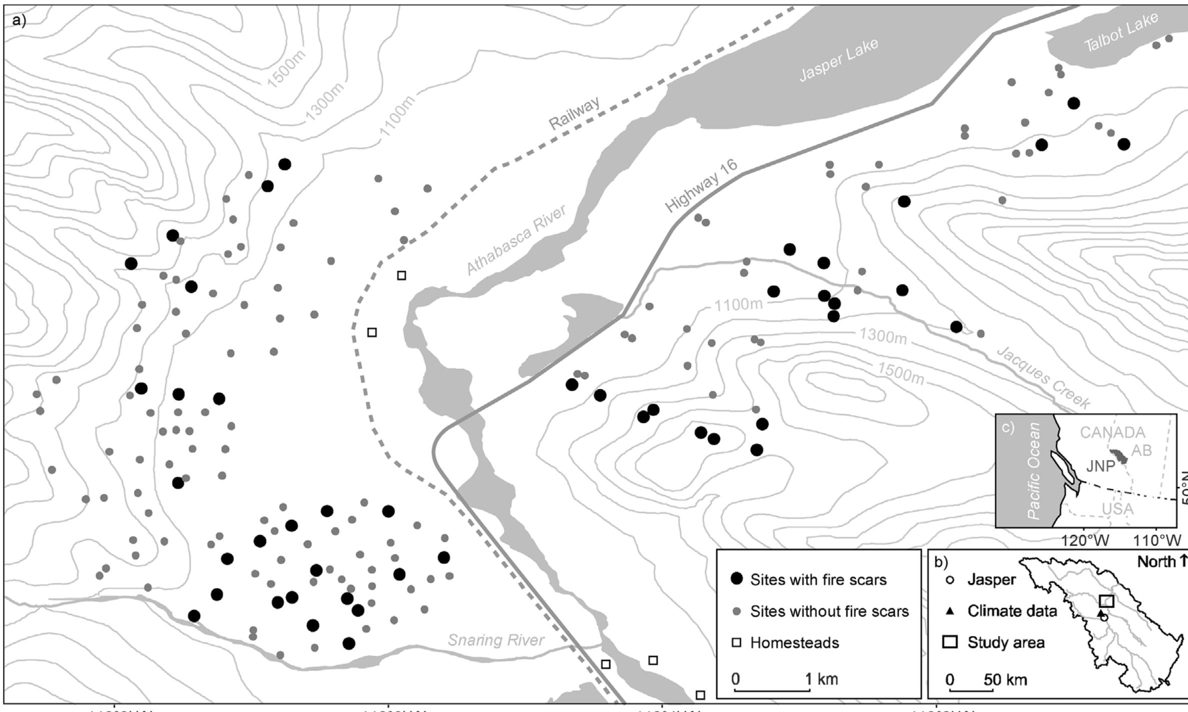

Fig. 1. a) Fire history plots (n = 172) in the Athabasca River valley of Jasper National Park (JNP). b) The study area is 12 km north of the town of Jasper and c) located in Alberta (AB), Canada. Climate data are for the midpoint between Pyramid and Patricia Lakes located 2.5 km northwest of the town of Jasper.

forests (Chavardès and Daniels, 2016) and increased closed-canopy forest cover at landscape scales (Rhemtulla et al., 2002). Whether changes in the fire regime and forest structures were caused by climate, human impacts, or both, remains undetermined.

In many forests of western North America, interannual to multidecadal climatic variation driven by atmospheric and oceanic circulation has been associated with dry conditions conducive to fire (Kitzberger et al., 2007; Trouet et al., 2006, 2010). The effects of these climatic drivers vary geographically, for example, the El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) have contrasting effects in the southern and northern Rocky Mountains (Schoennagel et al., 2005) and across the continental divide in Canada (Macias Fauria and Johnson, 2006). The effects of the Pacific North American pattern (PNA) extend across western North America (Trouet et al., 2006) and manifest at both interannual and multidecadal scales (Liu et al., 2017), with large fires associated with its positive mode during the 20th century across western North America (Trouet et al., 2006) and in the Canadian Rocky Mountains (Johnson and Wowchuck, 1993). Using Tande's (1979) record of historical fires in Jasper, derived from ring counts on fire-scarred trees, Schoennagel et al. (2005) showed large fires from 1700 to 1975 tended to burn during El Niño conditions coinciding with warm departures of the PDO. Although weak, this pattern is consistent with fire-climate relations in the northern Rockies and Pacific Northwest of the United States (Hessl et al., 2004; Gedalof et al., 2005; Heyerdahl et al., 2008a,b). At multidecadal scales, warm phases of the Atlantic Multidecadal Oscillation (AMO) interact with ENSO and PDO to synchronize historical fires across much of western North America (Kitzberger et al., 2007). To our knowledge, fire-climate relations have not been assessed using a crossdated fire record for Jasper National Park, nor has research on AMO effects extended this far north in the Rocky Mountains.

In some Canadian subalpine and boreal forests, reduced fire frequency has been explained by cooler and wetter climate starting in the mid-1700s and persisting through much of the 20th century (e.g., Johnson et al., 1990; Johnson and Larsen, 1991). In these forests, infrequent crown fires are ignited by lightning and burn large areas, with climate and weather affecting fuel combustibility and controlling fire occurrence, area burned, and severity (Macias Fauria and Johnson, 2008). Underlying this interpretation, historical and contemporary human impacts on the fire regime are assumed to be negligible (Johnson et al., 2001). However, recent research provides compelling evidence that fire suppression has significantly impacted even the crown-fire regimes at landscape scales in some subalpine and boreal forests (Kipfmueller and Baker, 2000; Cumming, 2005; Podur and Martell, 2009), including the Canadian Rocky Mountains (Wierzchowski et al., 2002; Van Wagner et al., 2006; Rogeau et al., 2016). The debate over human impacts on fire regimes, interactions with climate change, and their consequences for effective ecosystem management and restoration (Stephens et al., 2013; Moritz et al., 2014), highlights the need for ecosystem-specific understanding of historical fire regimes and their drivers.

In this study, we examined the role of climatic variation as a driver of historical fire occurrence in the montane forests of Jasper National Park. We present a fire-climate analysis using the first crossdated fire-scar record from a Canadian National Park in the Rocky Mountains. To compare with other research on fire-climate relations in western North America (Hessl et al., 2004; Schoennagel et al., 2005; Kitzberger et al., 2007; Heyerdahl et al., 2008a,b), we tested for associations between historical fire occurrence and tree-ring proxies of drought and interannual to multidecadal drivers of climatic variability. Secondly, we conducted tests to understand how local, historical drought was influenced by these climatic drivers. Ultimately, using both instrumental and proxy-climate records, we assessed whether climatic variation explained the absence of fire in our study area during the 20th century. We combined our results with the well-documented land-use history of Jasper to disentangle the relative importance of climate and humans to explain this observed disruption to the fire regime.

2. Materials and methods

2.1. Study area and research design

Our 3300-ha study area included montane (1000–1350 m above sea level (m.a.s.l.)) and lower subalpine (1350–1500 ma.s.l.) forests adjacent to the Athabasca River located north of the town of Jasper in Jasper National Park, Canada (Fig. 1). Forests in the study area are dominated by hybrid spruce (*Picea engelmannii* Parry x *Picea glauca* (Moench) Voss), lodgepole pine and interior Douglas-fir (Chavardès and Daniels, 2016). The instrumental records from 1971 to 2000 for the Jasper climate station (52°53′N, 118°04′W; 1062 m.a.s.l.; Environment Canada, 2015) show mean annual air temperature was 3.3 °C, with mean monthly temperatures of 15.0 and −9.2 °C for July and December, respectively. Mean annual precipitation averaged 399 mm, with 238 mm (60%) occurring as rain from May–September (Environment Canada, 2015). Despite the summer-wet precipitation regime, documentary fire records show that 86% of all lightning-ignited wildfires in Jasper National Park occurred during droughts in July and August between 1929 and 2012 (Parks Canada, 2013). The same records indicate only 6 lightning-ignited fires in our study area, all of which were suppressed before exceeding 1 ha.

Our research combines the fire-history datasets from two studies conducted in the study area. First, to quantify fire frequency, Rogeau (1999) created a time-since-fire map by delimiting patches of forests with distinct composition and structure on air photos at a scale of 1:40,000. Within 172 patches (Fig. 1), up to 8 trees were cored c. 30 cm above the ground to estimate the age of the oldest trees in a circular plot with a radius of 20 m. Each plot was searched for fire-scarred trees, snags, stumps and logs (hereafter, “scarred trees”) and a full cross-section was sampled from up to three scarred trees. Supplemental fire scars were sampled along patch boundaries. We acquired 38 of the fire-scarred samples for analysis in the current study. Second, as part of research on historical fire severity and frequency, Chavardès and Daniels (2016) resampled 29 of Rogeau’s (1999) plots. We cored 20 trees per plot c. 30 cm above the ground and sampled 64 additional fire-scarred trees from 1-ha search areas surrounding each plot centre.

2.2. Fire history analysis

All fire-scar and age samples were sanded following standard protocols (Stokes and Smiley, 1996). High-resolution (1200 or 2400 dots per inch) digital images were taken from the bark to the inner-most ring of cores, and along radii that included the scar tips on fire-scar samples. Using the program CooRecorder (Larsson, 2011), we measured ring widths, then visually crossdated and statistically verified ring dates using the programs CDendro (Larsson, 2011) and COFECHA (Holmes, 1983) to determine the years of the inner- and outer-most rings and individual fire scars. When possible, we differentiated early- or late-season fires from the location of the fire-scar tip within rings to assign an exact year to each fire (Dieterich and Swetnam, 1984). Dormant-season scars (e.g., along the boundary of two rings) that formed from 1895 to 1915 were designated early-season fires ($n = 3$), based on documentary evidence that homesteaders ignited fires in the spring in the study area (MacLaren, 2007; Murphy et al., 2007). Dormant season scars that formed prior to 1895 were designated late-season fires ($n = 7$), consistent with the timing of modern lightning-ignited wildfires during weather conducive to fire spread, although we acknowledge that people living or travelling in the area during this period may also have ignited fires in the spring and/or other seasons. Only fires crossdated with annual precision and recorded by ≥ 2 fire-scarred trees (hereafter, “fire years”) were included in subsequent analyses.

Since fire-susceptible lodgepole pine and hybrid spruce dominate our study area and are likely to be scarred or killed in a fire, we considered them potential recorders of fire throughout their lifespan. To estimate tree ages, inner-ring dates were corrected to account for the number of missed rings on cores that did not intercept the pith (5 ± 6 rings (mean ± standard deviation); Duncan, 1989) and the number of years for trees to grow to sampling height using species-specific age-height corrections (8 ± 5 rings; Powell et al., 2009). For each plot, the corrected age of the oldest tree indicated the beginning of the fire record; however, we did not assume these trees originated after fire and their ages were not used to calculate fire intervals.

Plot-specific fire-scar records were combined into a composite study-area fire record for fire-climate analyses. At the study-area scale, we used the crossdated fire-scar dates to determine the number of fire years, quantify the mean and range of fire intervals and the fire-free interval as the number of years since the last fire. The age of the oldest trees varied among plots so the potential to record fires also varied through time across the study area. Therefore, an annual fire index was calculated as the percentage of plots with fire-scarred trees relative to the number of plots with trees present that could have recorded fire in each year (Brown and Swetnam, 1994; Taylor et al., 2016). We estimated the probability of the fire-free interval occurring by chance (Whitlock and Schluter, 2015):

$$P\ (\text{fire free interval}) = (\text{annual probability of no fire scar forming})^{\text{length of fire-free interval}}$$

Where, the annual probability of a fire causing a scar somewhere in our study area is 1/mean fire interval and the probability of no fire scar forming is 1-(1/mean fire interval). The recurrence interval is 1/probability of the fire-free interval.

2.3. Local Douglas-fir chronology as a proxy of drought

We used a local Douglas-fir chronology as a proxy of drought since climate is spatially heterogeneous at fine spatial scales in the Canadian Rocky Mountains (Luckman, 1997; Luckman and Kavanagh, 2000). Watson and Luckman (2001, 2005) showed that Douglas-fir trees growing in montane forests of Jasper were limited by precipitation, making them a suitable proxy-indicator of local seasonal and annual drought. To assess climate-fire relations for our full fire record, we combined existing chronologies from Pyramid and Patricia Lakes (Ferguson and Parker, 1965; Watson and Luckman, 2001), and extended the chronology to 2011 using crossdated ring-width series from Douglas-fir sampled by Chavardès and Daniels (2016). Using the program COFECHA, we selected a subset of 81 ring-width series that were highly correlated (i.e., inter-series correlation = 0.806) and had no flagged segments, to create a new chronology representing Douglas-fir growth in our study area.

We conducted climate-growth analyses to verify that our newly extended Douglas-fir chronology was a suitable, temporally-stable proxy for growing season drought, consistent with reconstructions by Watson and Luckman (2001, 2005). Climate data were derived using ClimateNA, a program that uses bilinear interpolation and elevation adjustments to downscale baseline gridded climate data to scale-free point data (Wang et al., 2016). Monthly total precipitation, maximum and mean temperature records from 1901 to 2011 were derived for the midpoint between Pyramid and Patricia Lakes, which are less than one kilometre apart (52°54′N, 118°05′W; 1,182 ma.s.l.). We used these data to calculate monthly heat-moisture indices (Wang et al., 2012):

$$\text{Heat-moisture index}_{\text{monthly}} = (T_{\text{mean}} + 10)/(P/100)$$

Where, T_{mean} is the monthly mean temperature (°C) and P is monthly total precipitation (mm). Low moisture availability (e.g., drought), resulting from low precipitation and/or warm temperature, is indicated by high index values.

Individual crossdated ring-width series were detrended by fitting a negative exponential curve or linear regression to account for the non-climatic, age-related trend in ring widths using the program ARSTAN (Cook and Holmes, 1986). We compared climate-growth associations

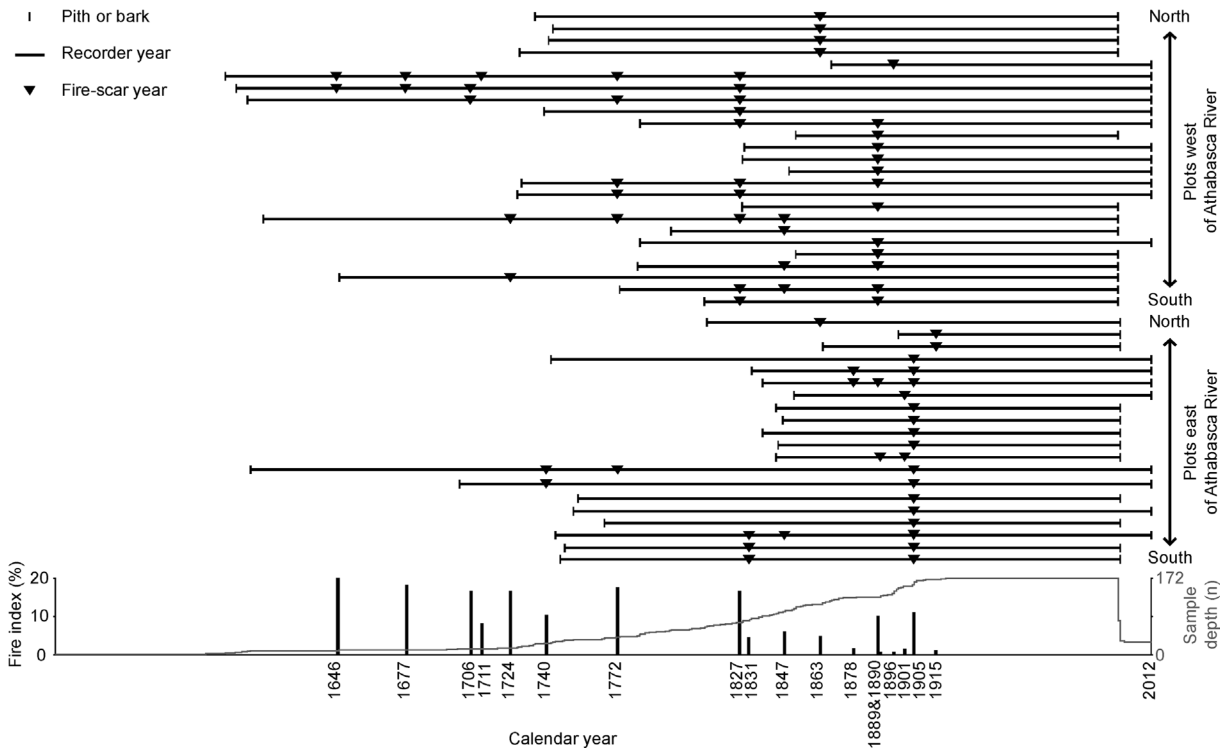

Fig. 2. Fire history records from the subset of 45 plots with fire-scarred trees (top) and the composite summary for all 172 plots in the study area (bottom). Horizontal lines represent individual plots. The length of each line represents the period of record, based on the crossdated pith date of the oldest tree through the year each plot was sampled (1997–2012). Triangles indicate crossdated fire-scar years. The composite fire record (bottom panel) shows the fire index, the percentage of plots recording fire (vertical bars) relative to the sample depth or number of plots potentially recording fire in each year (gray line).

between the resulting pre-whitened residual chronology and the modelled climate data using the program Dendroclim2002 (Biondi and Waikul, 2004). Pearson's correlation coefficients were calculated between ring-width indices and each of the monthly climate variables (monthly total precipitation, maximum and mean temperature, and heat-moisture indices). To assess lagged and direct climatic influences on tree growth, correlation coefficients were calculated for the 18-month window from the April prior to ring formation through September of the year each ring was formed. Confidence intervals were computed from 1000 bootstrapped samples (Biondi and Waikul, 2004). We confirmed the climate-growth associations between ring-width indices and each of the monthly climate variables were temporally stable using forward and backward evolutionary intervals with a base length of 36 years (Biondi and Waikul, 2004).

2.4. Climatic drivers of fire and local drought

Superposed epoch analysis (SEA) (Grissino-Mayer, 2001) was used to test for associations between fire occurrence from 1646 to 1915 and interannual climatic variation. We used our pre-whitened Douglas-fir residual chronology as a drought proxy, D'Arrigo et al.'s (2005a) tree-ring reconstruction of December–February sea surface temperatures in the NIñO3 region of the tropical Pacific as a proxy for ENSO, and Liu et al.'s (2017) tree-ring reconstruction of December–March atmospheric circulation over North America as a proxy for the PNA. The time series of NIñO3 and PNA were not white noise ($p < 0.0001$; SAS Proc Arima autocorrelation test for white noise using 6 lags, SAS Institute Incorporated, 2017). Therefore, to meet the assumptions of SEA, we prewhitened the NIñO3 and PNA time series by fitting autoregressive integrated moving average models based on lowest Akaike's information criterion and significant but uncorrelated parameter estimates (AR (2)) and used the white noise residuals in the SEA (white noise test $p = 0.571$ and 0.079, respectively; Heyerdahl et al., 2008b). For each proxy of climatic variation, we calculated mean values for fire years and each of the preceding three years and compared them to bootstrapped values derived from a Monte Carlo simulation of randomly selected years that provided 95%, 99%, and 99.9% confidence intervals (Grissino-Mayer, 2001).

To better understand drivers of drought in the context of historical fires in our study area, we extracted the ring-width index value for each fire year from the drought-sensitive Douglas-fir residual chronology. These indices represented the range of variation in drought under which historical fires burned. The mean of the 18 indices provided a quantitative criterion to identify other years in the chronology when drought was likely conducive to fire, even if fires did not burn. Taking a conservative approach, years with a ring-width index less than the mean for the 18 fire years were classified as "drought years"; all other years were "non-drought years". We repeated SEA, testing for associations between the 62 drought years from 1646 to 1915 and the NIñO3 and PNA white noise residuals. We used contingency tables to assess whether drought/non-drought years were associated with positive/negative annual departures of ENSO, PNA or PDO, and AMO indices, and their two- and three-way interactions. We repeated these tests for four different PDO reconstructions that encompassed the period 1646–1915 (Gedalof and Smith, 2001; D'Arrigo et al., 2005b; MacDonald and Case 2005; Shen et al., 2006). Significant departures between observed and expected values were determined using chi-square goodness-of-fit tests ($\alpha = 0.05$).

To determine if climatic conditions were conducive to fire during the 20th century, we identified drought years from 1916 to 2011 and verified them using climate data derived from ClimateNA. We compared annual (i.e., previous September to current August) total precipitation, mean maximum temperatures and mean heat-moisture indices during drought and non-drought years from 1916 to 2011 using Mann Whitney rank sum tests. Analysis of variance (ANOVA) on ranks and post hoc Dunn's tests compared mean ring-width indices of the 18 fire years, drought years from 1646 to 1915 (excluding fire years) and 1916–2011, versus non-drought years during the same two periods.

3. Results

3.1. Fire history

Fire-scarred trees were sampled from 45 of 172 plots distributed on both sides of the Athabasca River along the full elevation range (Fig. 1). The composite fire-scar record representing all plots in the study area included 18 fire years from 1646 to 1915 (Fig. 2), with a mean fire return interval of 16 ± 14 years (mean ± standard deviation; median = 13 years). A 54-year gap with no fire scars occurred between 1773 and 1826, inclusive, and no fire scars were recorded after 1915. The 96-year fire-free interval was 42 years longer than the maximum interval in the composite fire record. Given the mean fire return interval of 16 years, the annual probability of fire causing a scar somewhere in our study area is 0.0625 (e.g. 1/16); conversely, the annual probability of no fire is 0.9375 (e.g., 1–0.0625). The probability of 96 consecutive years without fire is 0.0020 (e.g., 0.9375^{96}), with a recurrence interval of 500 years (e.g., 1/0.0020).

3.2. Douglas-fir drought proxy

The Douglas-fir residual chronology was a suitable proxy for drought with narrow ring-width indices indicating drier and/or warmer than average years (Fig. 3). Positive correlations between radial growth and monthly precipitation from 1901 to 2011 were significant for the previous August, September, November and December, and current February, May and June. Correlations with monthly temperatures and heat-moisture indices were predominantly negative. The maximum temperature correlations were significant for the previous July and September and current January, May and June. Similarly, heat-moisture correlations were significant for the previous July to August and current March, May and June. Climate-growth relations were most stable through time for current May precipitation and current May and June heat-moisture indices (not shown).

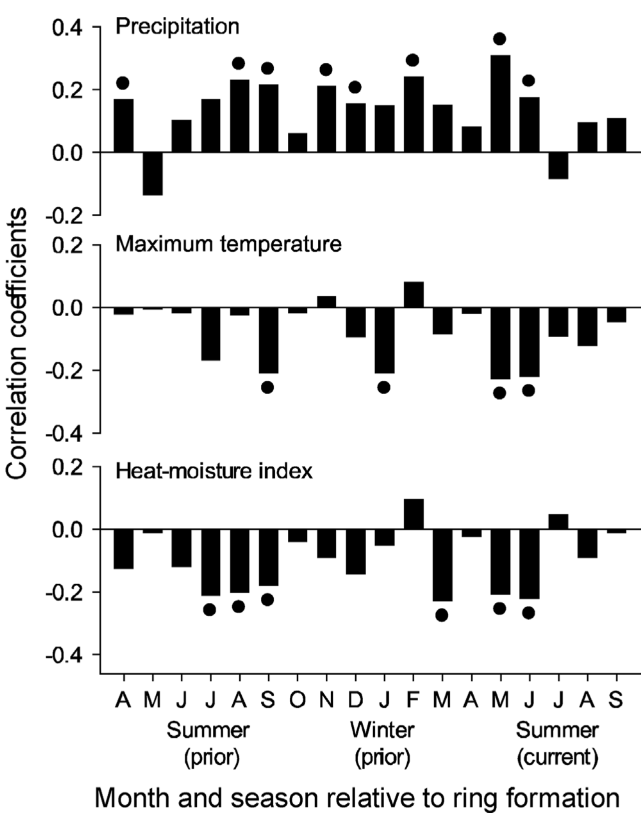

Fig. 3. Climate-growth relations for Douglas-fir from 1901 to 2011. Bars are the correlation function coefficients between the Douglas-fir residual chronology and monthly precipitation, maximum temperature, and heat-moisture indices. Dots indicate significant correlations ($\alpha = 0.05$).

3.3. Fire and drought relations

Climatic conditions varied during the 18 fire years from 1646 to 1915 (Fig. 4); nevertheless, fire years were significantly associated with drought indicated by narrow ring-width indices in the Douglas-fir residual chronology ($p < 0.01$; Fig. 5). Ring-width indices antecedent to fire years were not significantly different from average. We detected no significant associations between fire years and the reconstructions of NIñO3 and PNA.

The 62 drought years from 1646 to 1915 (Fig. 4) were significantly associated with positive NIñO3 indices ($p < 0.05$), consistent with El Niño conditions (D'Arrigo et al., 2005a), and with positive PNA indices ($p < 0.001$; Fig. 5). Two years prior to drought were significantly associated with negative NIñO3 indices ($p < 0.01$), consistent with La Niña conditions (D'Arrigo et al., 2005a). Among the four PDO indices, the strongest association was with MacDonald and Case's (2005) reconstruction (shown in Fig. 4), although it was not significant ($p = 0.085$). Chi-square goodness-of-fit tests confirmed that drought years were associated with positive NIñO3 ($p < 0.009$), PNA ($p < 0.002$), and their two-way interaction ($p < 0.001$). NIñO3 dominated the two-way interactions with all PDO indices ($p \le 0.04$) and the AMO index ($p = 0.018$). NIñO3 also dominated three-way interactions, none of which were significant ($p \le 0.108$) except the interaction with Gedalof and Smith's (2001) PDO reconstruction ($p = 0.007$). NIñO3 and PNA dominated the three-way interaction with AMO ($p < 0.001$).

From 1916–2011 there were 17 drought years, although no fires were recorded. Annual precipitation was significantly less during drought years relative to non-drought years after 1915 ($p = 0.009$), but heat-moisture and maximum temperature did not differ significantly between drought and non-drought years ($p = 0.051$ and $p = 0.117$, respectively). The ring-width indices for drought years from 1646 to 1915 (0.54 ± 0.15) and 1916–2011 (0.59 ± 0.10) were lower than, but not significantly different from, the indices during the 18 fire years (0.73 ± 0.28); indices were significantly larger during non-drought years, before and after 1915 (1.13 ± 0.26 and 1.06 ± 0.24, respectively; $p < 0.05$).

4. Discussion

4.1. Climatic drivers of historical fires and drought in Jasper

Our composite fire-scar record for the montane and lower subalpine forests in Jasper National Park included 18 fire years between 1646 and 1915. In previous research, Chavardès and Daniels (2016) showed that these fires were of mixed-severity, generating fire scars and even-aged cohorts of trees within and among fires. These historical fires burned during a range of climatic conditions, but were predominantly associated with drought indicated by our Douglas-fir chronology. In our study area, narrow rings result from warm, dry conditions in May and June, plus the prior July through September and interceding winter months. Although fire years were associated with narrow Douglas-fir rings in the year of fire but not antecedent years, the lagged climate-growth relations suggest that warm, dry summers that precede warm, dry springs also contribute to the drying of fuels that can combust in the advent of a spreading fire.

Although historical fires in our study area were significantly associated with drought, the majority of drought years lacked fire scars. Even in warm, dry years, ignitions must occur in suitable fuels and during weather conducive to fire spread (Gedalof, 2011); such ignitions may have limited historical fire occurrence. We also acknowledge that an absence of fire scars must be interpreted cautiously as it does not necessarily equate with absence of fire (Falk et al., 2011). Lack of scars

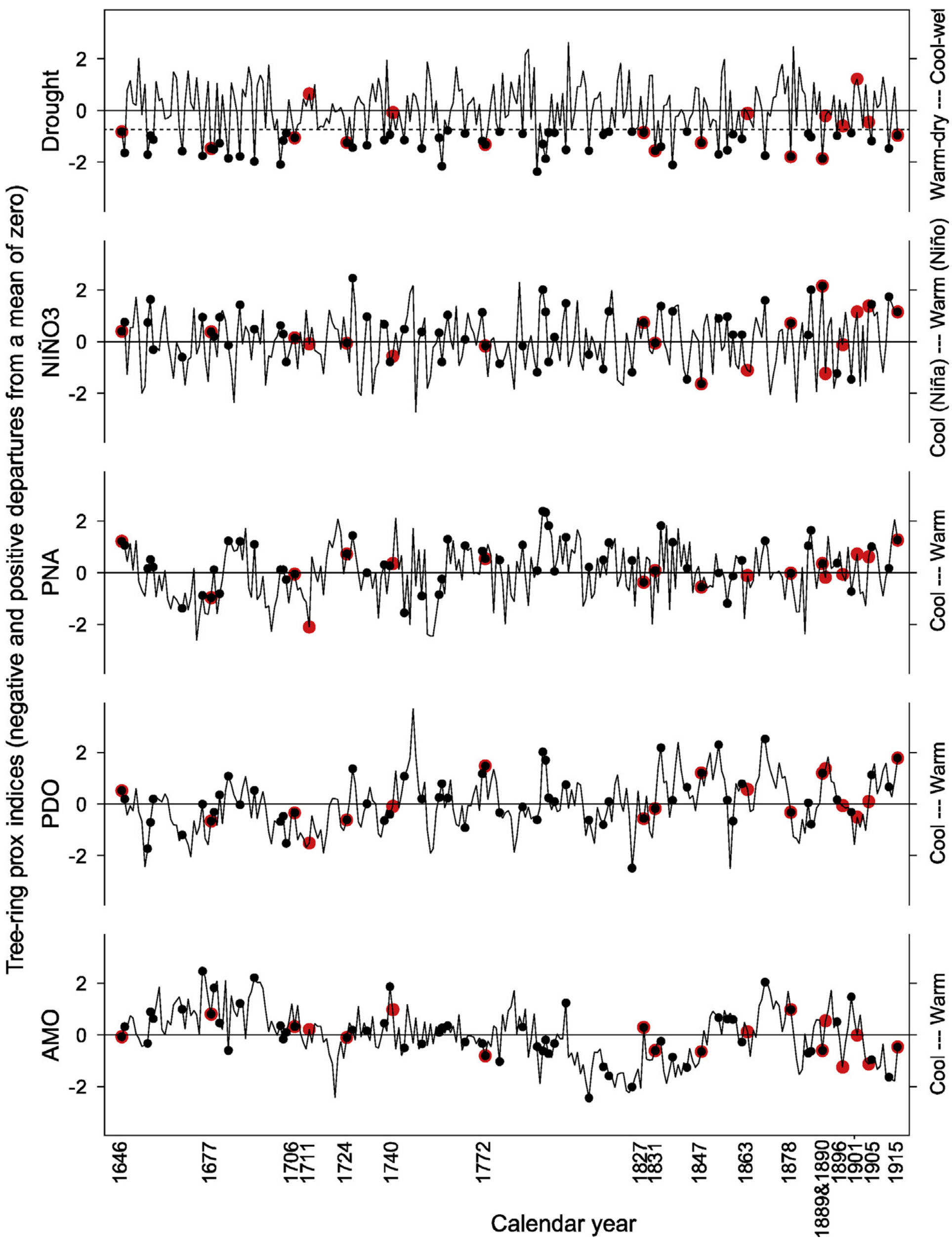

Fig. 4. Fire (n = 18; red dots) and drought (n = 62; black dots) years from 1646 to 1915 relative to interannual to multidecadal climate variation. The Douglas-fir residual ring-width chronology represents drought (top). The dashed horizontal line indicates mean index value for the 18 fire years; years with index values less than or equal to the mean are drought years. The remaining panels are tree-ring proxies for NIÑO3 (D'Arrigo et al., 2005a), PNA (Liu et al., 2017), PDO (MacDonald and Case, 2006), and AMO (Gray et al., 2004).

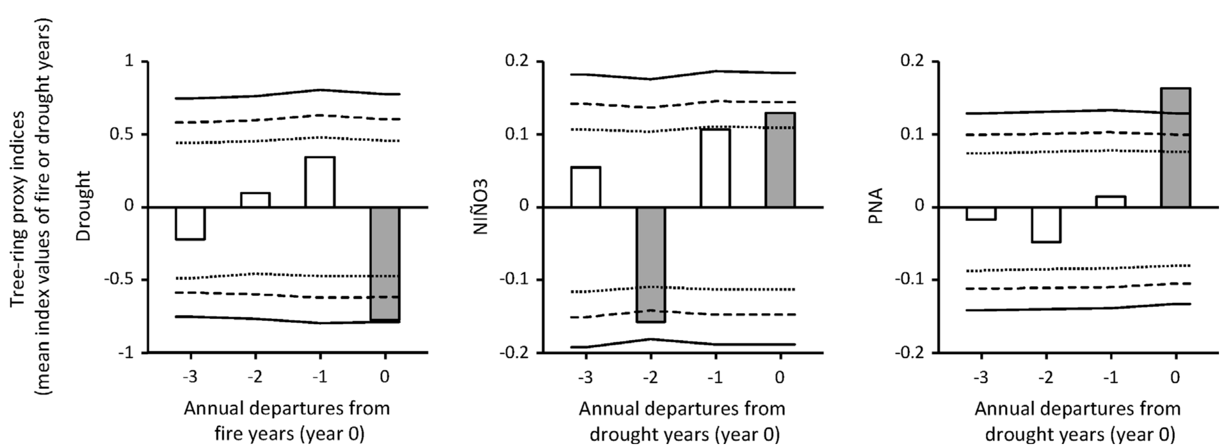

Fig. 5. Superposed epoch analyses showing significant associations between fire years (n = 18), and drought represented by the Douglas-fir residual chronology (left) and between drought years (n = 62) and the tree-ring proxies for NIÑO3 (D'Arrigo et al., 2005a; middle) and PNA (Liu et al., 2017; right). Solid, long- and short-dashed lines represent confidence intervals of 99.9%, 99%, and 95%, respectively. Grey bars indicate statistically significant departures from the mean ($p < 0.05$).

can result from isolated or small fires, very low- or high-severity fires that leave few scars, or depletion of fire scar evidence through time (Swetnam et al., 1999, 2011; Parsons et al., 2007). In attempt to overcome these potential limitations, we sampled living and dead fire-scarred trees in 1 plot per 20 ha (on average) across our 3300-ha study area to develop a long and spatially comprehensive fire record.

In our fire record, seven fires burned during non-drought years, including two fires in 1711 and 1901 that burned in wetter-than-average years. In relatively wet years, ignitions may be sustained following several consecutive days of dry weather resulting from blocking high pressure and low precipitation, which dry fuels sufficiently to sustain fire (Nash and Johnson, 1996; Macias Fauria and Johnson, 2008). Alternatively, written, oral and archaeological records document human use of fire by people to create forage and facilitate hunting in the montane forests of Jasper (Murphy et al., 2007). Human ignitions may have been intentionally set during years when the fire would be predictable and easy to control, analogous to modern prescribed fires that are ignited during a limited range of fire weather conditions (Ryan et al., 2013).

Fire-climate relations with interannual and multidecadal climate were less clear, in part, because our fire record included only 18 fires, which limited the statistical power to discern significant drivers and their interactions. Given the significant association we detected between fire and drought, we investigated the climatic drivers of drought in our study area as an alternative approach for understanding the factors influencing historical fire risk and potential occurrence. On average, drought years occurred during positive departures of the NIñO3 indices, consistent with Niño conditions, and positive departures of the PNA indices. For the NIñO3 index, the negative departures two years prior to drought likely reflect the oscillation between La Niña and El Niño conditions (Trenberth, 1997), rather than a need for antecedent moist conditions to increase surface fuels to sustain fire as observed in the dry climate of the southwestern United States of America (USA) (Swetnam and Betancourt, 1990). Combined, our findings relating fire and drought and those relating drought with interannual drivers, suggest that drought is a necessary but not sufficient condition for fire occurrence in the study area, as found elsewhere in the Pacific Northwest (Gedalof, 2011).

In the Canadian Cordillera, including the central Rockies of Alberta, effects of the positive mode of the PNA (Johnson and Wowchuck, 1993; Macias Fauria and Johnson, 2008, 2008) and El Niños (Moore and McKendry, 1996; St. Jacques et al., 2013) are similar to effects in the inland Northwest of the USA where shallow snow packs and early melt, result in prolonged growing seasons that are more likely to have droughts (Cayan et al., 1999). The PNA's positive mode was related to blocking high pressure anomalies over the Rocky Mountains (Macias Fauria and Johnson, 2008; Liu et al., 2017) that increase spring and summer drought and were related to fire occurrence in western North America (Trouet et al., 2006) including the Canadian Rockies (Johnson and Wowchuck, 1993). Similarly, in the Pacific Northwest of the USA (Heyerdahl et al., 2008b; Kitzberger et al., 2007) and some parts of the Canadian Rockies (Mori 2011) drought and fires have been related to El Niños concurrent with positive departures of the PDO and/or AMO. Yet, in our study, we did not find significant associations between fires and these coarse-scale modes of climate variability. Instead we found significant associations between local droughts, positive El Niño and PNA conditions, but we did not find similar associations with the PDO and AMO in Jasper. We hypothesize the lack of association is because Jasper is located along the boundary of two regional climate patterns with contrasting PDO influences, west and east of the Rocky Mountains (Macias Fauria and Johnson, 2006). Along climatic transition zones, the effects of the PDO may be weakened or inconsistent through time so that the additive effects of ENSO and PDO are diminished, as documented at the transition zone at c. 45°N latitude in the western USA (Westerling and Swetnam, 2003; Hessl et al., 2004; Trouet et al., 2006). Likewise, the AMO had no discernible effect on historical fires or droughts in Jasper possibly because it lies near a climatic transition zone for the AMO. Kitzberger et al. (2007) found warm AMO phases were related to higher-than-expected fire synchrony over western North America except in the Pacific Northwest and Sierra Nevada where cool AMO phases produced a lower degree of synchrony with positive PDO and El Niño conditions.

4.2. Variation in historical fire occurrence over 350 years

The long-term variation in our fire-scar record has several similarities with other fire history reconstructions in western North America. In the montane forests of Jasper, we found: (1) a declining number of fire scars prior to 1772; (2) no fire scars between 1773 and 1826; (3) frequent fire scars between 1827 and 1915; and (4) no fire scars after 1915. Below, we discuss this variation in relation to methodological constraints, climatic variation, and land-use change to discern the relative influences of climate and humans in Jasper.

The earliest part of our fire-scar record from 1646 to 1772 included seven fires, averaging one fire every 18 years, a conservative estimate of fire occurrence. During this period, 38 plots included thin-barked, fire-susceptible trees that established prior to 1773 and 9 plots (24%) included fire-scarred trees with exposed cambium making them susceptible to subsequent fires. Even with these potential recorder trees present, it is possible that more fires burned during this period but evidence is missing due to successive fires or wood decay, an inherent limitation of fire-scar studies (Swetnam et al., 1999).

The 53 years from 1773 to 1826 with no fire scars is consistent with the "fire gap" documented by several reconstructions in western North America (Trouet et al., 2006; Kitzberger et al., 2007). Kitzberger et al. (2007) attributed this gap to broad-scale climatic variation linked to a pronounced cold phase of the AMO; however, we did not detect a statistical association between the AMO and historical fires or droughts in Jasper. We cannot definitively rule out interactions among climatic drivers due to the small number of fires in our record. Alternative explanations for the fire gap include reduced lightning ignitions related to variation in weather and climate (Van Wagner et al., 2006), reduced cultural ignitions following the 1781–2 smallpox epidemic that affected indigenous people in our study area (Payne, 2007), changes in vegetation that limited fire spread and scar formation (Marlon et al., 2012), or random variation in fire occurrence (Wierzchowski et al., 2002).

Fires were most frequent from 1827 to 1915, when one fire burned every nine years, on average. High fire frequency in the 19th and early-20th centuries in other North and South American forests has been attributed to the conservation of fire-scar evidence, forest and climatic conditions favourable to fire following the fire gap, and changes in land-use and ignitions associated with settlement by Europeans (Taylor and Skinner, 1998; Guyette et al., 2002; Veblen et al., 1999, 2000, Jensen and McPherson, 2008). Interpreting human impacts in western North American forests shows that the timing of colonial impacts on fire regimes depends on local history. For example, colonial impacts on fire frequency began c.1620 in the southwestern USA (Liebmann et al., 2016), but was delayed until c.1775 in the Sierra Nevada of California (Taylor et al., 2016). Further north in the Canadian Rocky Mountains, European influences via the fur trade, exploration, missions and settlement in Jasper were delayed until the 1800s (Murphy et al., 2007). Written documents from early European explorers confirm oral histories that the mountain passes through Jasper were important transportation and trade corridors and indigenous people used the montane forests surrounding the Athabasca River for hunting (Thompson, 1916). Trade outposts were established in the early 1800s and, by 1846, 54 people were permanently living around the Jasper House outpost, just north of our study area (De Smet, 1905). Henry John Moberly, of dual indigenous and European ancestry, was among the first residents and his extended family remained until the early 20th century (Murphy, 2007). Non-indigenous homesteading did not start until 1895 with the Swift family, but stopped c. 1910 when Jasper National Park was

created (Payne, 2007). Thus, human impacts via trade, colonialism, and settlement likely had the greatest impacts on fire occurrence in the late 19th and early 20th centuries in our study area.

In stark contrast, no fire scars were recorded after 1915, although the likelihood of recording fires was greatest and climate was often favourable. The lack of fire scars at all 172 plots for 96 consecutive years from 1916 to 2011 was unprecedented in our fire record. We conservatively estimated a 0.0020 probability of this fire-free interval occurring by chance. These calculations assumed fires are temporally independent; however, we acknowledge that the probability of a fire scarring trees may increase through time as fuels accumulate. Conversely, the probability of no fire would decrease through time. If so, the probability of the 96-year fire-free interval would be < 0.0020 and the recurrence interval would exceed 500 years. These results suggests that it is > 99% probable that the absence of fire scars after 1915 indicates a change in the fire regime.

4.3. Drivers of 20th century change

Climatic variation alone does not explain the absence of fire scars in the montane forests of Jasper National Park since 1915. Tree-ring proxy indicators of drought and instrumental records include variable climatic conditions during the 20th century, including multiple years with significantly below-average precipitation similar to conditions in which historical fires burned. Compared to earlier periods, the lack of fire scars after 1915 was consistent with the decline in fire frequency starting in the late-1800s at sub-continental to global scales (Marlon et al., 2008, 2012). In many areas of western North America, widespread agricultural development and livestock grazing indirectly impacted fire regimes by reducing fuels and fire spread (Marlon et al., 2012; Liebmann et al., 2016; Swetnam et al., 2016; Taylor et al., 2016); however, these forms of land use were not permitted once Jasper National Park was created. Instead, we suggest human impacts on the fire regime in Jasper were more direct.

There is strong, corroborating evidence of human impacts on rates of fire ignition, followed by fire management policies implemented in Jasper after 1915. Prior to the 20th century, human ignitions may have been necessary in addition to lightning to sustain the fire regime east of the continental divide in Jasper (Wierzchowski et al., 2002). Oral and archaeological records document human use of fire over centuries, and written records describe spring ignitions by local families to create forage and facilitate hunting between 1895 and 1910 (Murphy, 2007; Murphy et al., 2007). After 1913, the displacement of local people, prohibition of fire use, and implementation of a fire protection and suppression policy effectively eliminated fire from Jasper (Murphy et al., 2007). Over time, enhanced fire-fighting training, initial attack strategies, improved access, and modern equipment have increased the capacity to detect and rapidly suppress fires. As a testament to these efforts, fire records from Jasper National Park include 101 lightning-ignitions since 1940, only eight of which resulted in fires > 40 ha in size (Parks Canada, 2013). Moreover, the six wildfires ignited by lightning within the boundaries of our study area were suppressed before they exceeded 1 ha in size (Parks Canada, 2013). Combined, these lines of evidence lead us to conclude that reduced human ignitions combined with active fire suppression superseded climatic variation to explain the absence of fire scars in our study area since 1915.

4.4. Conclusions and management implications

Interannual climatic variation and 20th century human influences on fire ignition and spread explained the temporal variation in the historical mixed-severity fire regime of the montane forests in Jasper National Park. From 1646 to 1915, 18 fires burned mainly during drier than average years. No fire scars formed after 1915 although all 172 study plots included trees that could have recorded fire and climate was conducive to fire during multiple years according to our tree-ring proxy climate of drought and instrumental records. Our conclusion that human influences superseded climatic variation to explain the lack of fire scars during the 20th century is substantiated by Park records on land use and fire suppression. In absence of fire, contiguous closed-canopy forests have increased and homogenized the landscape (Rhemtulla et al., 2002; Chavardès and Daniels, 2016). The cumulative effects of fire suppression, projected climate change including longer fire seasons with enhanced summer drought (Flannigan et al., 2003; Wotton et al., 2017), and the recent expansion of mountain pine beetle (*Dendroctonus ponderosae* Hopkins) into Jasper National Park driving high levels of tree mortality (Jasper National Park, 2016), have important implications for future wildfire effects and management. Our findings support ongoing proactive management by Parks Canada to counter the effects of a century of fire suppression and resulting deviation from historical fire regimes and ecosystem function. Ongoing management includes mechanical thinning as a surrogate for surface fires to reduce fuels, prescribed fires, and managed wildfires where safe to do so (Parks Canada and the Canadian Parks Council, 2008). We recommend the efficacy of these management options be monitored to ensure they enhance landscape-level forest diversity and resilience to climate change.

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